I "ZLM Stat" - Measurement Software for Statistical Analyses

The "ZLM Stat" program module lets you measure and analyse both position and angle data of an object to be tested. The module works in conjunction with distance and angle optics of standard or extra-high resolution, as well as with 2m or 10m straightness optics. ZLM Stat is primarily used if the object under test is to be positioned to a number of points several times each, in order to yield statistical information about the positioning process. Compared with the "ZLM Position", "ZLM Angle (static)" and "ZLM Straightness" modules (sections G and H of this manual), "ZLM Stat" offers the advantage that measurement data can be acquired along several axes of a multi-axis laser interferometer in synchronism. The parameter to be measured and the optics to be used can be chosen independently for each axis.

I 1 Standard measurement and analysis procedures

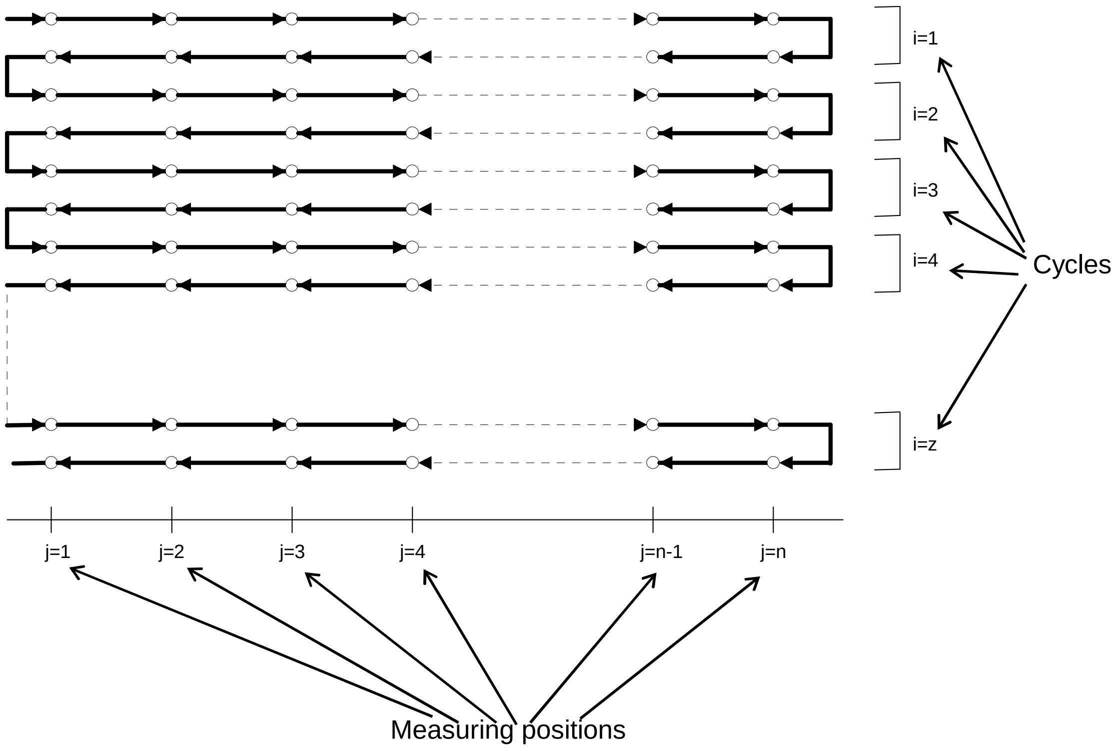
The information on positioning methods and standard data analysis procedures given in this section is similar to the information in section G about the "ZLM Position" calibration software.
The positioning and analysis procedures described there can also be used with several measurement axes. The relevant standards describe statistical analysis methods only for distance measurements, but these methods can be generalized for application to rotatory quantities and transverse deviations.

I 1.1 Positioning methods

In order to yield statistical information on its positioning behaviour, the object under test must be moved to a number of positions several times. Among the positioning methods used in practice, the program supports the linear, unidirectional linear, oscillation (also called "pendulum-step") and quasi-pilgrim step ("quasi-pilger") methods. To facilitate understanding, the positioning sequences are described as applied to linear measurements, but they can also be applied to rotation axes; the program will support such application.

I 1.1.1 Linear method

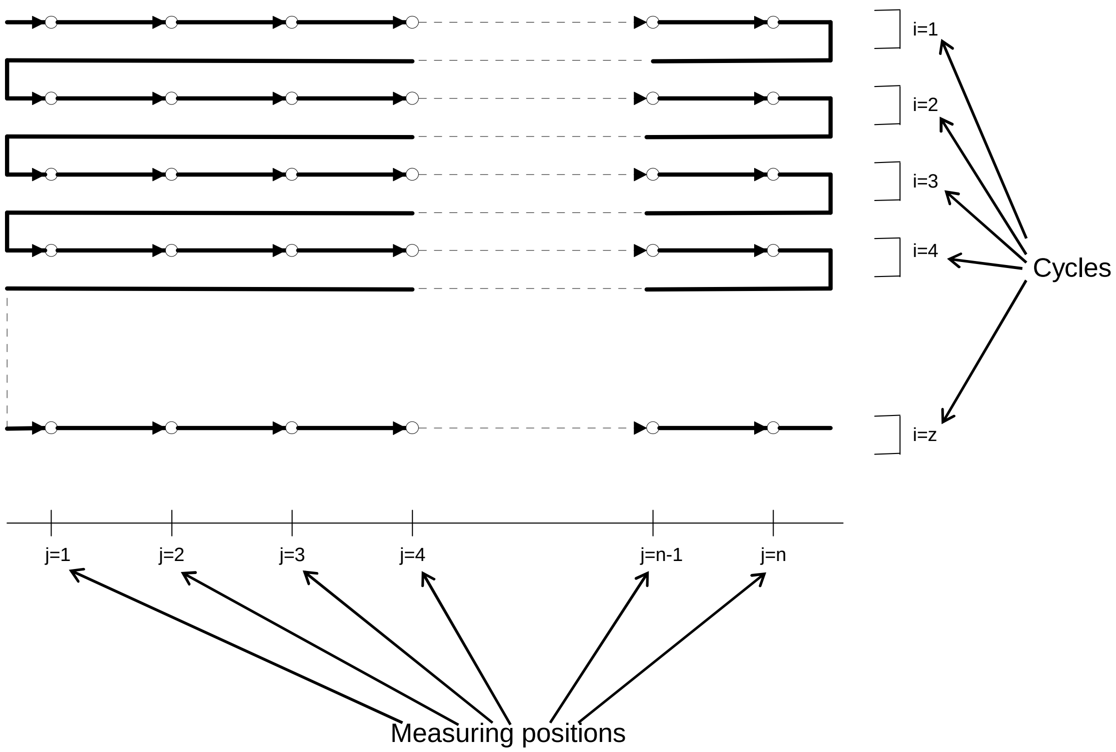
With the linear method, all positions are first travelled to in succession in the positive direction and then again in succession in the negative direction. The whole procedure is repeated several times (cycles).



In order to ensure that the first and last positions in each cycle are travelled to from the correct direction, it is necessary to provide an approach length at the start of the procedure, and a return loop at the end of each half-cycle.

This positioning method is easy to program. With great distances between positions, however, the total measurement takes considerable time. Greater temperature variations during that time will affect both the backlash error (reversal span) and the position spread (see section I 1.2).

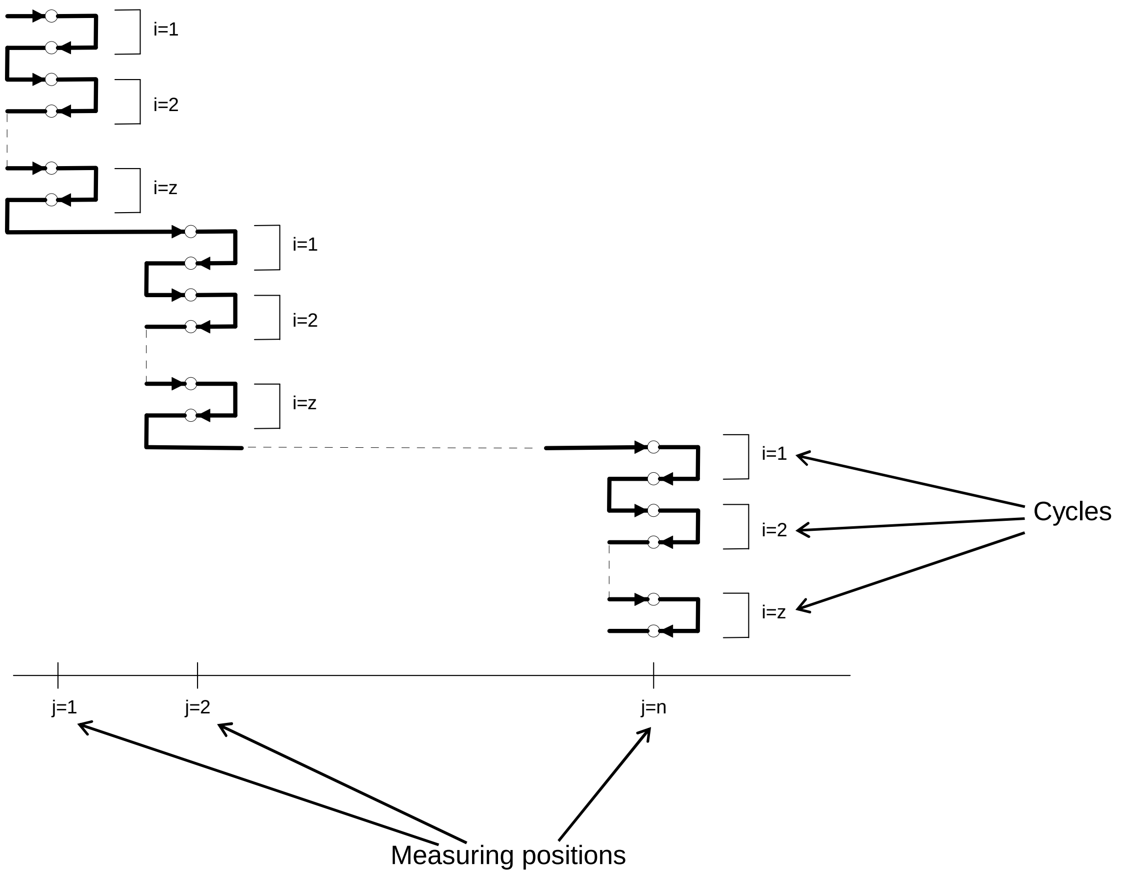
I 1.1.2 Unidirectional linear method



If it can be assumed that the differences between positioning in positive and positioning in negative directions are negligible (i.e. a small backlash error (reversal span)), the unidirectional linear method suggests itself.

In an extreme case one might also make a single-cycle rapid test.
Mind, however, that the standard analysis procedures issued by the standardization bodies (described in section I 1.2) do not provide for this positioning method.

I 1.1.3 Oscillation ("Pendulum-step") method

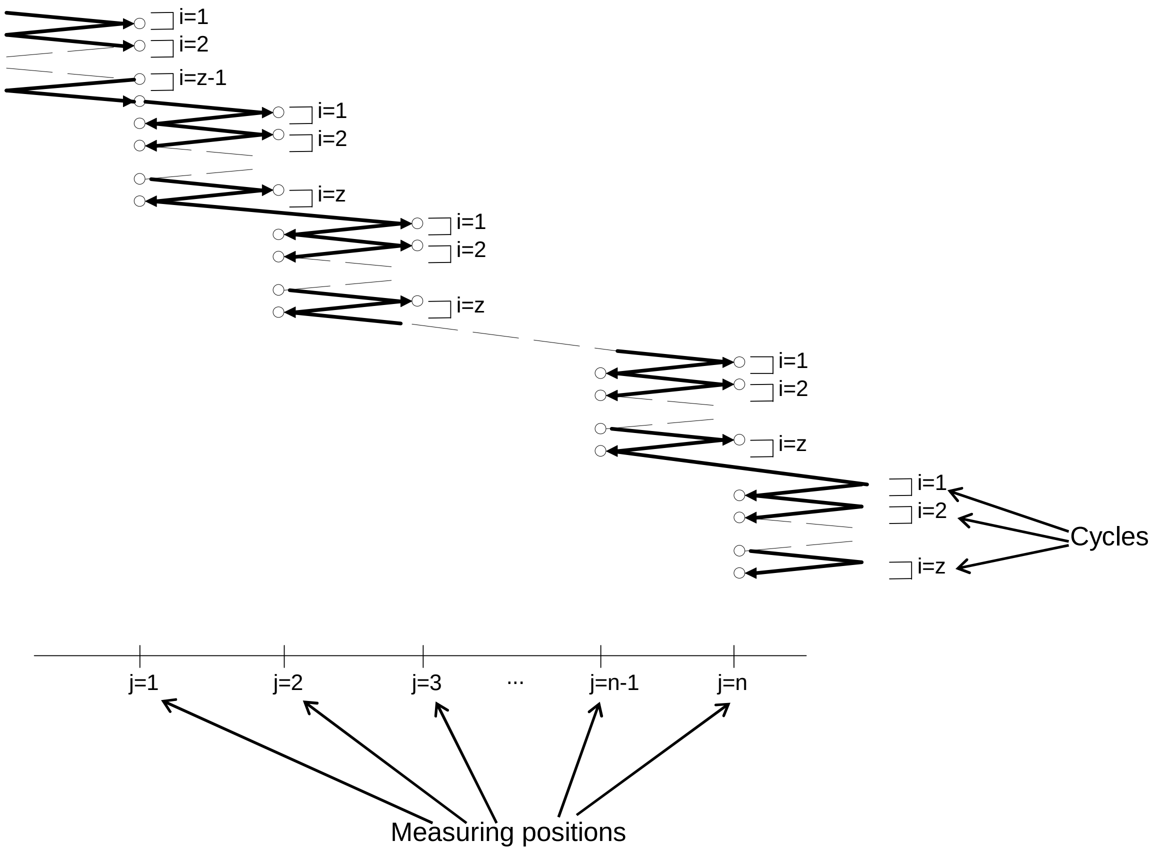


With this method, each measurement position is repeatedly travelled to, alternatingly from the positive and negative directions, before the measurement proceeds with the next position.

Of all the methods described, the Oscillation method involves the shortest total length of travel. This is of advantage especially where the positions are spaced far apart.

Major temperature variations during the measurement affect neither the backlash error (reversal span) nor the position spread (see sect. I 1.2). However, because of the long time passed between measuring the first and measuring the last position, thermal and other influences occurring during that time enter the measurement as systematic errors.

I 1.2.4 Quasi-pilgrim step ("Quasi-pilger") method



With this method, the first measurement position is travelled to several times in positive direction. Next, alternating travels are performed to the second position in positive direction and to the first position in negative direction. The pattern of alternating travels to the j^{th} and $(j+1)^{th}$ positions is continued until the last position has been travelled to repeatedly in the positive direction. Finally, the last position needs to be travelled to repeatedly in the negative direction.

Same as with the Oscillation method, great temperature variations during the measurement do not affect the backlash error (reversal span) nor the position spread, but enter the measurement as systematic errors.

I 1.2 Standard analysis procedures

Several standards authorities and institutions have issued standards and recommendations for the inspection of coordinate measuring machines and machine-tools.

The "ZLM Stat" measuring program is designed for the inspection of coordinate measuring machines and machine-tools in accordance with the following standards,

- ISO 230
- VDI/DGQ 3441
- NMTBA

for the inspection of machine tools, and

- VDI/VDE 2617

for the inspection of coordinate measuring machines.

The standards mainly differ by the computation of parameters and the graphical presentation of the results.

All these standards deal with position measurements. VDI/VDE 2617 also covers straightness and angle measurements, but does not describe any methods of statistical analysis for such measurements. The "ZLM Stat" program module supplies diagrams and parameters for straightness and angle measurements that closely follow the analysis methods described for position measurements. The overview charts in this section, however, contain only those analysis equations that are described in the standards.

Objective of measurement in inspecting machine-tools: Assessment of the accuracy to which components can be machined

Objective of measurement in inspecting coordinate measuring machines: Assessment of the machine's measuring accuracy

Result of a measurement: Relevant standards define parameters and recommend graphs by which the systematic and random deviations from the ideal state of a machine can be assessed. The present program supplies these parameters and diagrams as results of measurements.

For the acquisition of measurement data, the following points should be minded:

- Establish at least one line parallel to each machine axis of interest, along which measurement positions can be moved to.
- Measurement positions should be distributed throughout the range of travel.

Further recommendations on selecting measurement positions are given by the standards quoted.

Standard	Minimum number, absolute	Minimum number per scale element	Equation for establishing nominal positions
ISO 230	5 (for measured lengths up to 1 m) 5 per metre (for measured lengths up to 2 m)	1	$P_j = N \cdot p \cdot r$ P_j - nominal position N - integer r - random decimal fraction p - greatest period
VDI/DGQ 3441	10 per metre + 1 (for measured lengths up to 2 m)	1	
VDI/VDE 2617	11	2	

The relevant standards and recommendations differ greatly in their procedures of computing the parameters and in their modes of presenting the result graphically.

What they all have in common is that they define a set of parameters that separately characterize
- systematic position deviations,
- random position deviations, and
- composite (systematic plus random) deviations.

These three kinds of parameters can also be obtained separately from the graphs established according to all the standards concerned.

Let the significance of the parameters be explained by the example of a machine-tool:

Systematic position deviations:

The standards concerned, except ISO 230, define a **"Position deviation"**. With a certain quantity of like parts being machined on a machine-tool, the "Position deviation" indicates the average machining error to be expected for the parts.

The standards concerned, except for NMTBA, specify a **"Backlash"** (ISO) or **"Reversal span"** (the other standards). The "Backlash" or "Reversal span" indicates the average effect to be expected if in the machining process a position is travelled to from one position instead of the other.

Random position deviations:

The **"Position spread"** indicates the maximum differences to be expected in at least 99.5% of the machined parts. (As an exception, VDI/VDE 2617 specifies the position spread for coordinate measuring machines, computed for 95% of the reading errors to be expected.)

Composite position deviations:

The **"Position uncertainty"** indicates the machining error to be expected in a 99.5% yield, irrespective of the positioning direction.

The charts on the following pages show how the parameters and graphs are computed according to the different standards.

VDI/DGQ 3441	z - Number of measuring cycles n - Number of positions i - Cycle number j - Position number	x_{ij} - Deviation (actual-nominal) at position j during cycle i $\uparrow$ - Positive travel direction $\downarrow$ - Negative travel direction

Diagram:

Average deviation:

$$\bar{x}_j\uparrow = \frac{1}{z}\sum_{i=1}^{z} x_{ij}\uparrow \qquad \bar{x}_j\downarrow = \frac{1}{z}\sum_{i=1}^{z} x_{ij}\downarrow \qquad \bar{x}_j = \frac{\bar{x}_j\uparrow + \bar{x}_j\downarrow}{2}$$

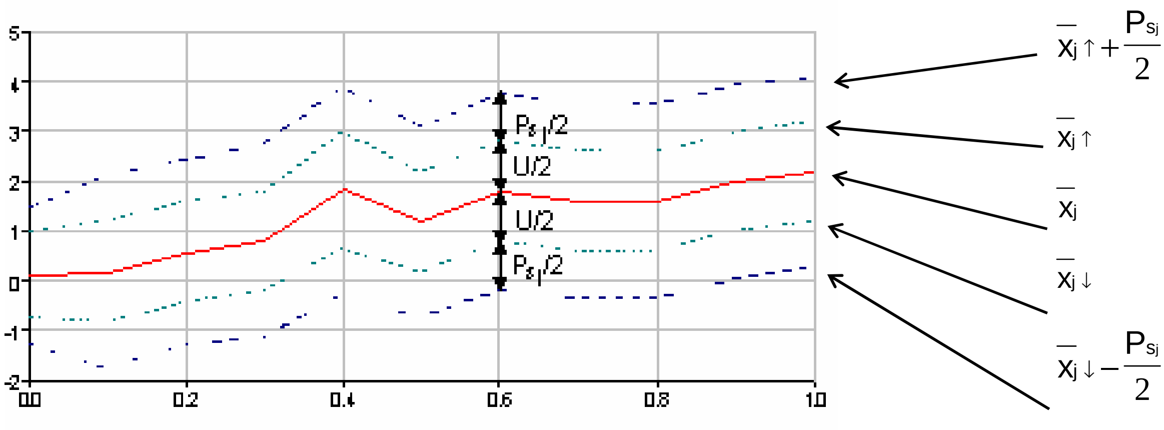
Position spread:

$$P_{sj} = 3\bullet\left(\sqrt{\frac{1}{z-1}\sum_{i=1}^{z}(x_{ij}\uparrow - \bar{x}_j\uparrow)^2} + \sqrt{\frac{1}{z-1}\sum_{i=1}^{z}(x_{ij}\downarrow - \bar{x}_j\downarrow)^2}\right)$$

Reversal span:

$$U_j = \left|\bar{x}_j\uparrow - \bar{x}_j\downarrow\right|$$

Deviation (micrometers)



Target position (metres)

Parameters:

Position spread

$$P_{s\,max} = \max\left[P_{sj}\right]_{j=1}^{n} \qquad P_{s\,mit} = \frac{1}{n}\sum_{j=1}^{n} P_{sj}$$

Reversal span

$$U_{max} = \max\left[U_j\right]_{j=1}^{n} \qquad U_{mit} = \frac{1}{n}\sum_{j=1}^{n} U_j$$

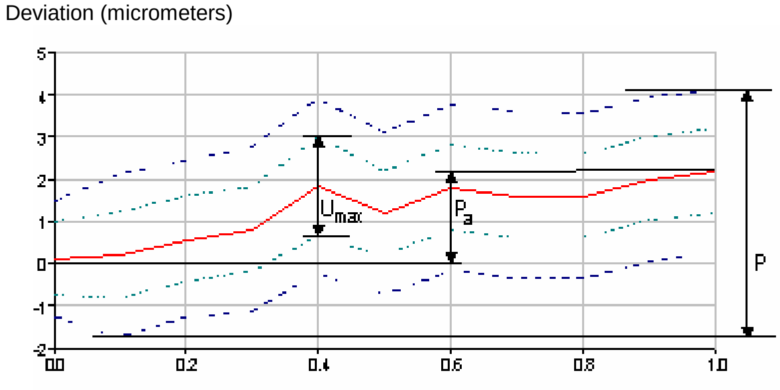
Position deviation

$$P_a = \left| \max\left[\bar{x}_j\right]_{j=1}^{n} - \min\left[\bar{x}_j\right]_{j=1}^{n} \right|$$

Position uncertainty

$$P = \max\left[\bar{x}_j + \frac{1}{2}(U_j + P_{sj})\right]_{j=1}^{n} - \min\left[\bar{x}_j - \frac{1}{2}(U_j + P_{sj})\right]_{j=1}^{n}$$

Deviation (micrometers)



Target position (metres)

VDI/VDE 2617	z - Number of cycles n - Number of positions i - Cycle number j - Position number	x_{ij} - Deviation (actual-nominal) at position j during cycle i ↑ - Positive travel direction ↓ - Negative travel direction

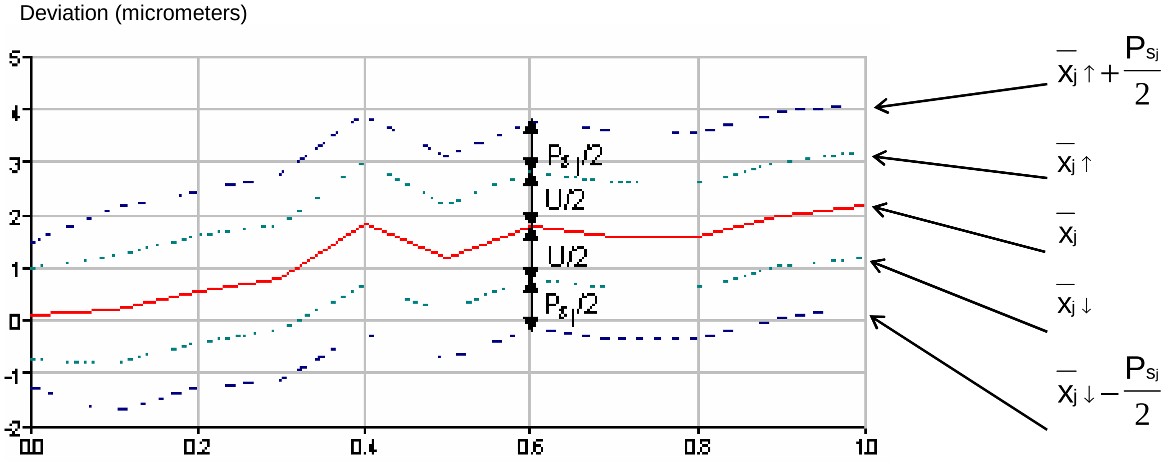
Diagram:

Average deviation: $\overline{x}_j\uparrow = \frac{1}{z}\sum_{i=1}^{z} x_{ij}\uparrow$ $\quad \overline{x}_j\downarrow = \frac{1}{z}\sum_{i=1}^{z} x_{ij}\downarrow$ $\quad \overline{x}_j = \frac{\overline{x}_j\uparrow + \overline{x}_j\downarrow}{2}$

Position spread: $P_{sj} = 2\bullet\left(\sqrt{\frac{1}{z-1}\sum_{i=1}^{z}(x_{ij}\uparrow - \overline{x}_j\uparrow)^2} + \sqrt{\frac{1}{z-1}\sum_{i=1}^{z}(x_{ij}\downarrow - \overline{x}_j\downarrow)^2}\right)$

Reversal span: $U_j = \left|\overline{x}_j\uparrow - \overline{x}_j\downarrow\right|$

Deviation (micrometers)



Target position (metres)

Parameters:

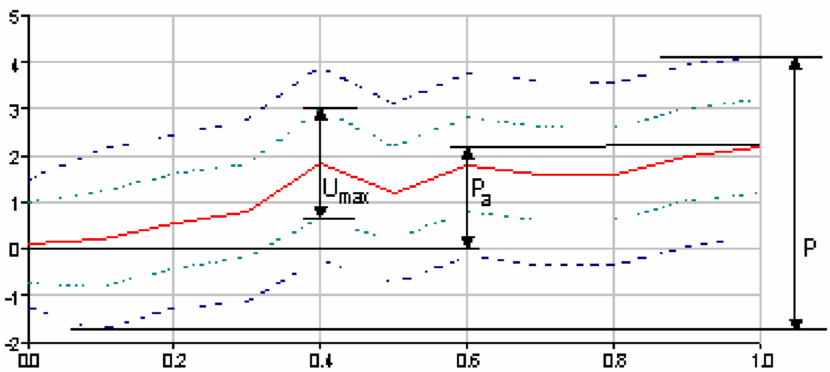
Position spread: $P_{s\,max} = \max\left[P_{sj}\right]_{j=1}^{n}$ $\quad P_{s\ mit} = \frac{1}{n}\sum_{j=1}^{n} P_{sj}$

Reversal span: $U_{max} = \max\left[U_j\right]_{j=1}^{n}$ $\quad U_{mit} = \frac{1}{n}\sum_{j=1}^{n} U_j$

Position deviation: $P_a = \left|\ \max\left[\overline{x}_j\right]_{j=1}^{n} - \min\left[\overline{x}_j\right]_{j=1}^{n}\ \right|$

Position uncertainty: $P = \max\left[\overline{x}_j + \frac{1}{2}(U_j + P_{sj})\right]_{j=1}^{n} - \min\left[\overline{x}_j - \frac{1}{2}(U_j + P_{sj})\right]_{j=1}^{n}$

Deviation (micrometers)



Target position (metres)

ISO 230	z - Number of cycles n - Number of positions i - Cycle number j - Position number	x_{ij} - Deviation (actual-nominal) at position j during cycle i ↑ - Positive travel direction ↓ - Negative travel direction

Diagrams:

Average deviations

$$\bar{x}_j\downarrow = \frac{1}{z}\sum_{i=1}^{z} x_{ij}\downarrow$$

$$\bar{x}_j\uparrow = \frac{1}{z}\sum_{i=1}^{z} x_{ij}\uparrow$$

Repeatability

Standard deviation:

$$s_j\uparrow = \sqrt{\frac{1}{z-1}\sum_{i=1}^{z}(x_{ij}\uparrow - \bar{x}_j\uparrow)^2}$$

$$s_j\downarrow = \sqrt{\frac{1}{z-1}\sum_{i=1}^{z}(x_{ij}\downarrow - \bar{x}_j\downarrow)^2}$$

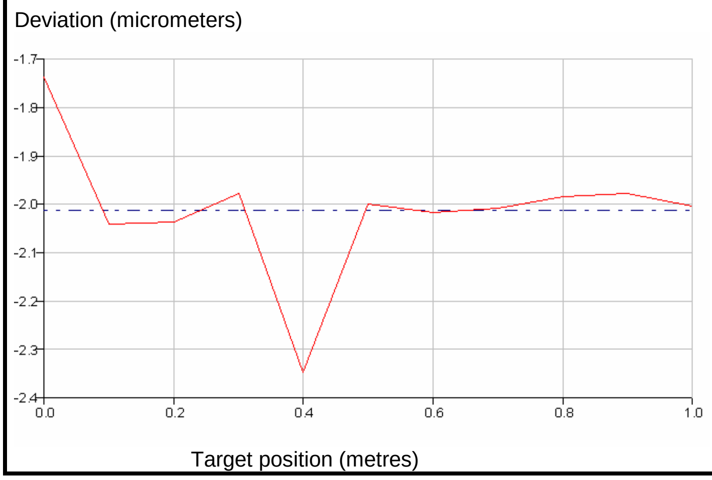
$\bar{x}_j\downarrow + 3s_j\downarrow$

$\bar{x}_j\downarrow - 3s_j\downarrow$

$\bar{x}_j\uparrow + 3s_j\uparrow$

$\bar{x}_j\uparrow - 3s_j\uparrow$

Backlash



$$B_j = \bar{x}_j\downarrow - \bar{x}_j\uparrow$$

$$\bar{B} = \frac{1}{n}\sum_{j=1}^{n} B_j$$

ISO 230	z - Number of cycles n - Number of positions i - Cycle number j - Position number	x_{ij} - Deviation (actual-nominal) at position j during cycle i $\uparrow$ - Positive travel direction $\downarrow$ - Negative travel direction

Parameters:

Repeatability

$$R = \max\left[\max\left[6s_j\uparrow, 6s_j\downarrow, 3s_j\uparrow + 3s_j\downarrow + \left|B_j\right|\right]\right]_{j=1}^{n}$$

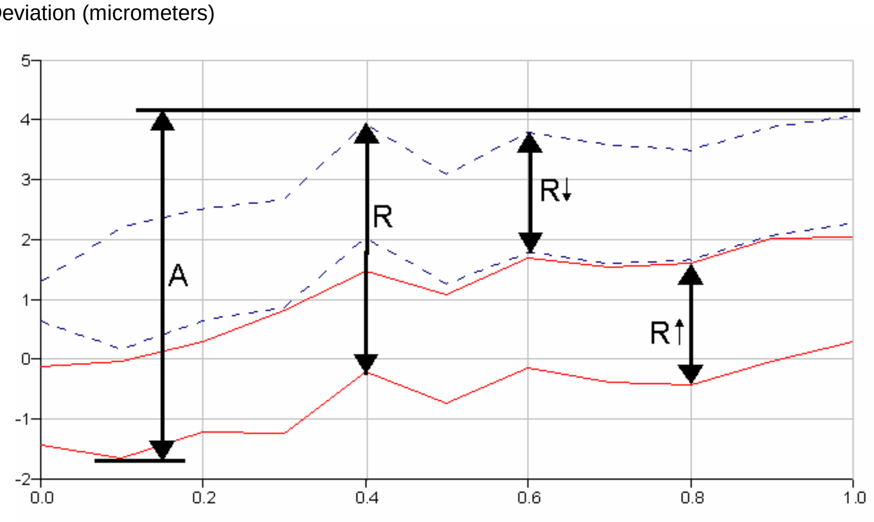
$$R\uparrow = \max\left[6s_j\uparrow\right]_{j=1}^{n}$$

$$R\downarrow = \max\left[6s_j\downarrow\right]_{j=1}^{n}$$

Accuracy

$$A = \max\left[\max\left[\bar{x}_j\uparrow + 3sj\uparrow, \bar{x}_j\downarrow + 3sj\downarrow\right]\right]_{j=1}^{n} - \min\left[\min\left[\bar{x}_j\uparrow - 3sj\uparrow, \bar{x}_j\downarrow - 3sj\downarrow\right]\right]_{j=1}^{n}$$

Deviation (micrometers)

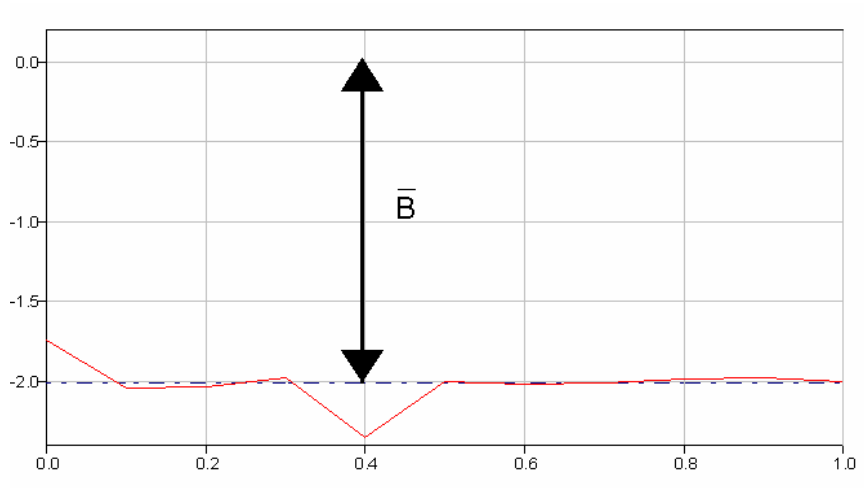


Target position (metres)

Mean backlash

$$\bar{B} = \frac{1}{n}\sum_{j=1}^{n}\left(x_j\downarrow - x_j\uparrow\right)$$

Deviation (micrometers)



Target position (metres)

NMTBA	z - Number of cycles n - Number of positions i - Cycle number j - Position number	x_{ij} - Deviation (actual-nominal) at position j during cycle i $\uparrow$ - Positive travel direction $\downarrow$ - Negative travel direction

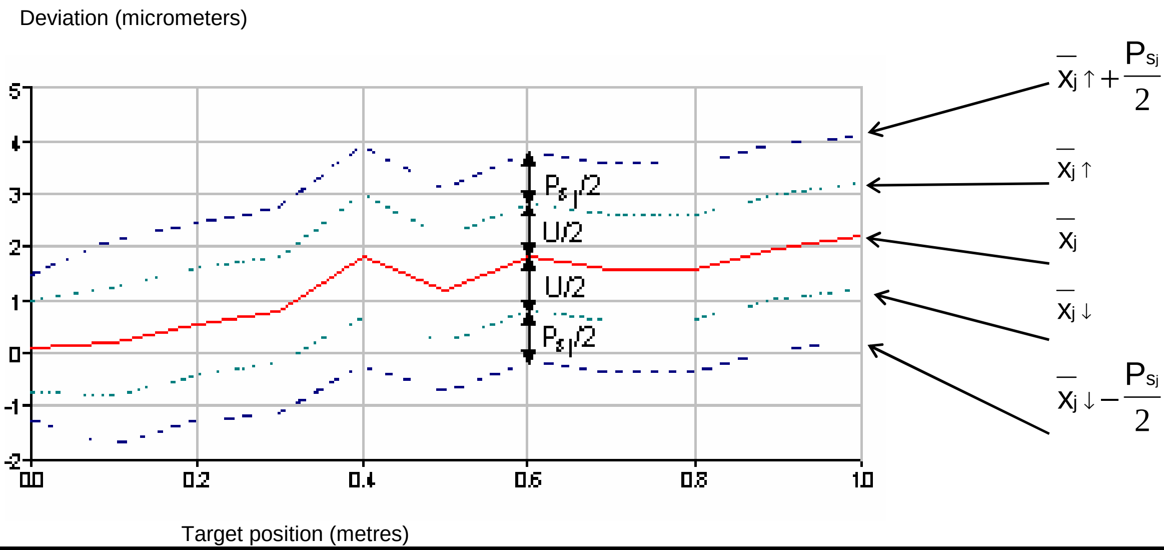
Diagram:

Average deviation:

$$\overline{x}_j = \frac{1}{2\cdot z}\sum_{i=1}^{z}\left(x_{ij}\uparrow + x_{ij}\downarrow\right)$$

Position spread:

$$P_{sj} = 6\bullet\sqrt{\frac{1}{2\cdot z\text{-}1}\sum_{i=1}^{z}\left\{\left(x_{ij}\uparrow - \overline{x}_j\right)^2 + \left(x_{ij}\downarrow - \overline{x}_j\right)^2\right\}}$$



Parameters:

Position spread

$$P_{s\,max} = \max\left[P_{sj}\right]_{j=1}^{n} \qquad P_{s\,mit} = \frac{1}{n}\sum_{j=1}^{n}P_{sj}$$

Offset

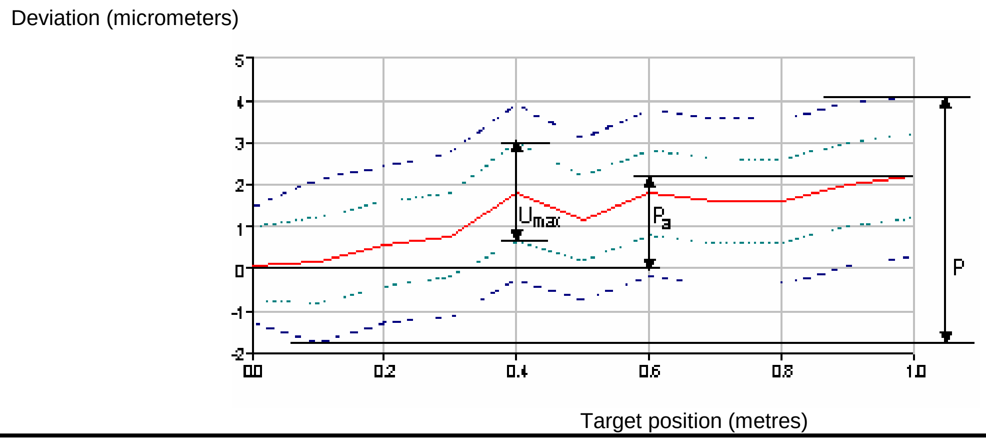
$$O = -\frac{1}{2}\bullet\left(\max\left[\overline{x}_j + \frac{P_{sj}}{2}\right]_{j=1}^{n} + \min\left[\overline{x}_j - \frac{P_{sj}}{2}\right]_{j=1}^{n}\right)$$

Position deviation

$$P_a = \left|\ \max\left[\overline{x}_j\right]_{j=1}^{n} - \min\left[\overline{x}_j\right]_{j=1}^{n}\ \right|$$

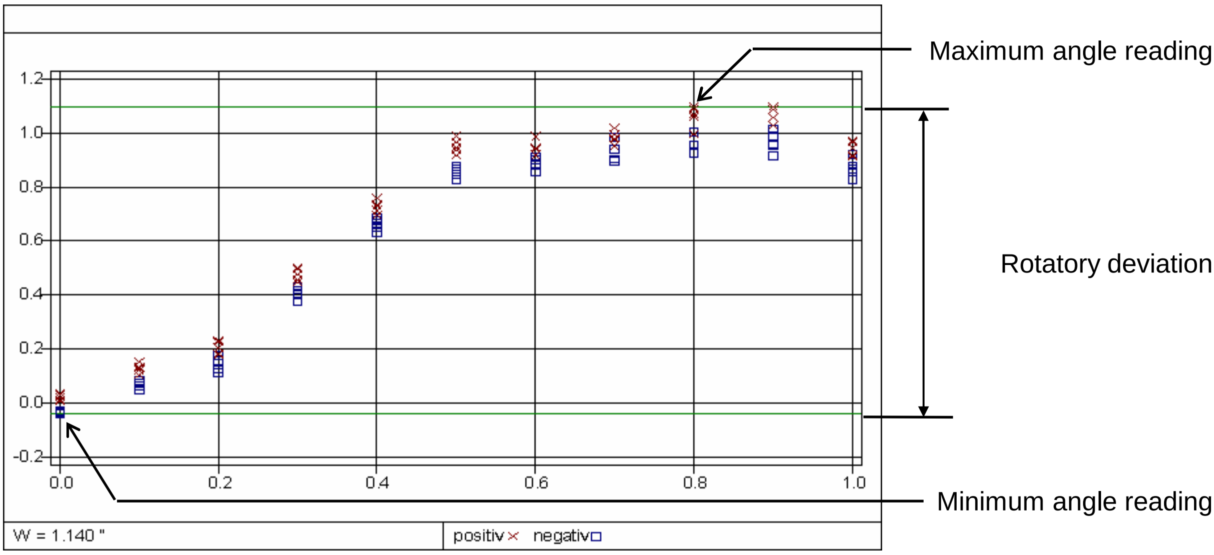
Position uncertainty

$$P = \max\left[\overline{x}_j + \frac{P_{sj}}{2}\right]_{j=1}^{n} - \min\left[\overline{x}_j - \frac{P_{sj}}{2}\right]_{j=1}^{n}$$



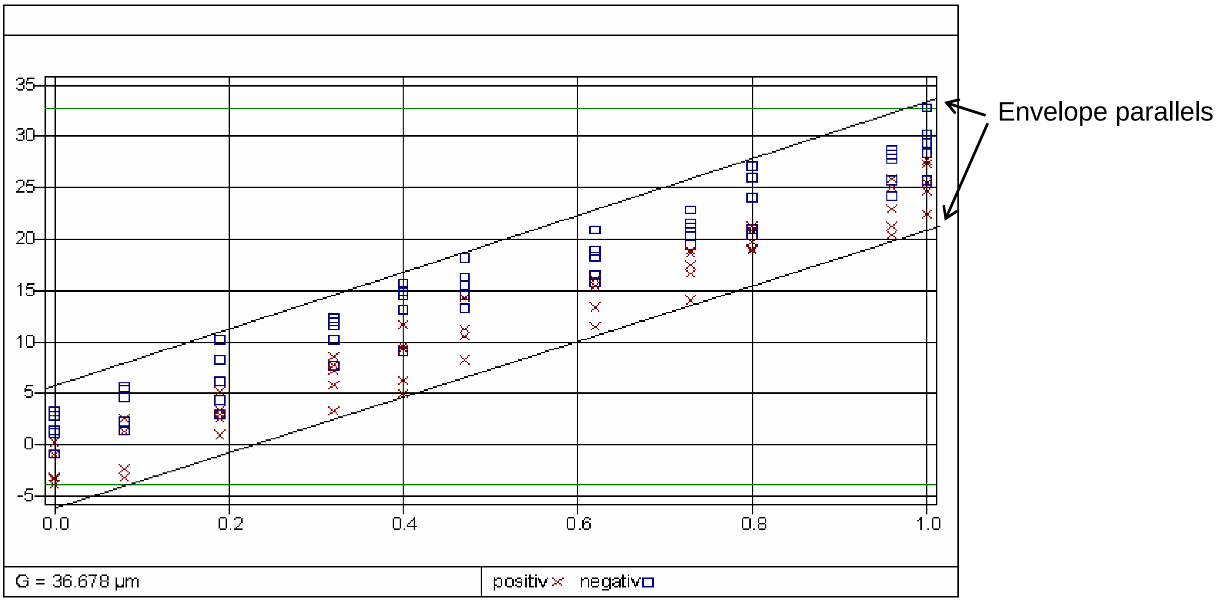
In addition to the statistical analysis of position measurements, ISO 230 specifies procedures for determining **"Rotatory deviations"** and **"Straightness deviations"**.

In an angle measurement, a number of angle readings are taken at each measuring position. The "Rotatory deviation A" is the difference between the greatest and smallest of all angle readings taken, irrespective of the position and travel direction.

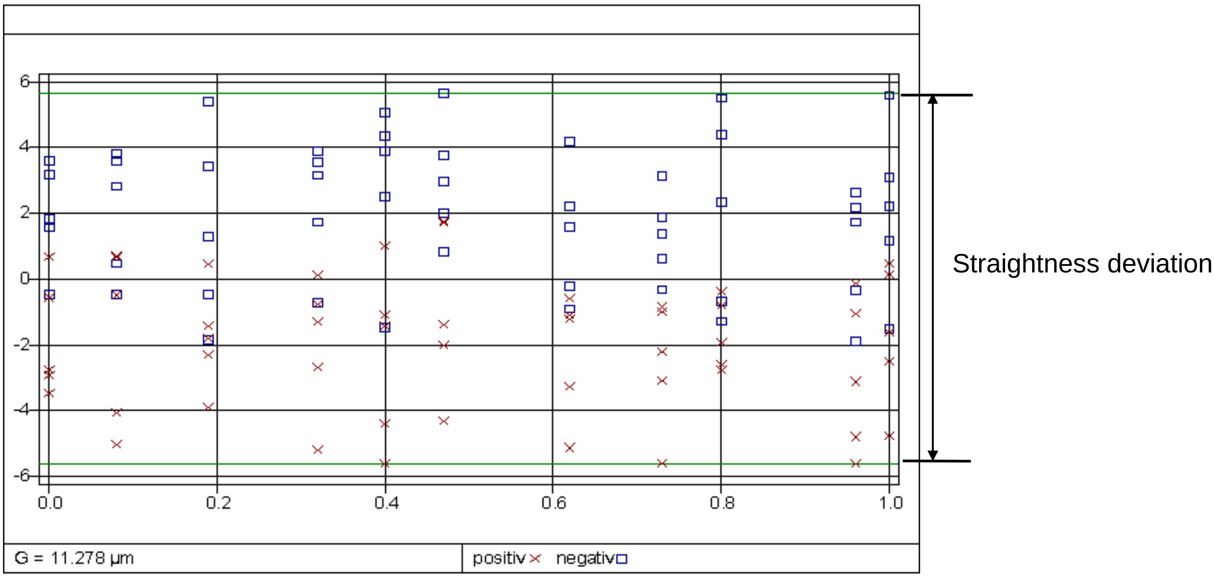


In a straightness measurement, the laser beam usually is not exactly aligned with the axis being measured. This would cause major errors if the difference between maximum and minimum readings were defined as a parameter.

Therefore, a "Straightness deviation S" has been defined as the distance between two parallels that include between them all measuring points while having the minimum possible distance from one another. The program calls these straight lines "envelope parallels".



When fitting the envelope parallels, the program transforms all readings in such a way that after transformation the two lines are approximately parallel with the ordinate axis.



The program also offers a least-squares fitting procedure, in which a straight line is determined for which the sum of the squares of distances from the line is minimum. This procedure, too, is followed by a transformation aimed at placing the straight line in parallel with the ordinate axis. But in this case, the difference between maximum and minimum is always either greater than or equal to the difference between maximum and minimum in envelope parallel fitting.